Wire-Cell Tomographic Event Reconstruction for Large LArTPCs

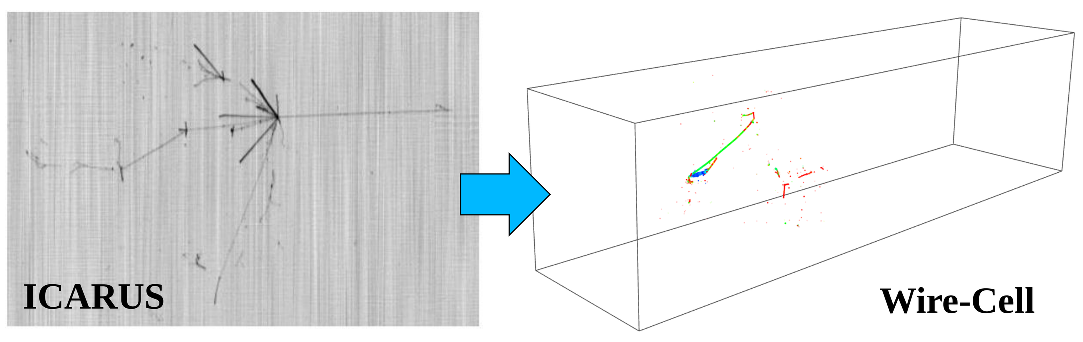
http://www.phy.bnl.gov/wire-cell/

Xin Qian, Brett Viren, and Chao Zhang

Brookhaven National Laboratory

Introduction

Event reconstruction is one of the most challenging tasks in analyzing the data from current and future large liquid argon time projection chambers (LArTPCs). The performance of the event reconstruction holds the key to many potential future discoveries with the LArTPC technology such as searching for new CP violation in the leptonic sector, determining the neutrino mass ordering, and searching for additional light (sterile) neutrino species.

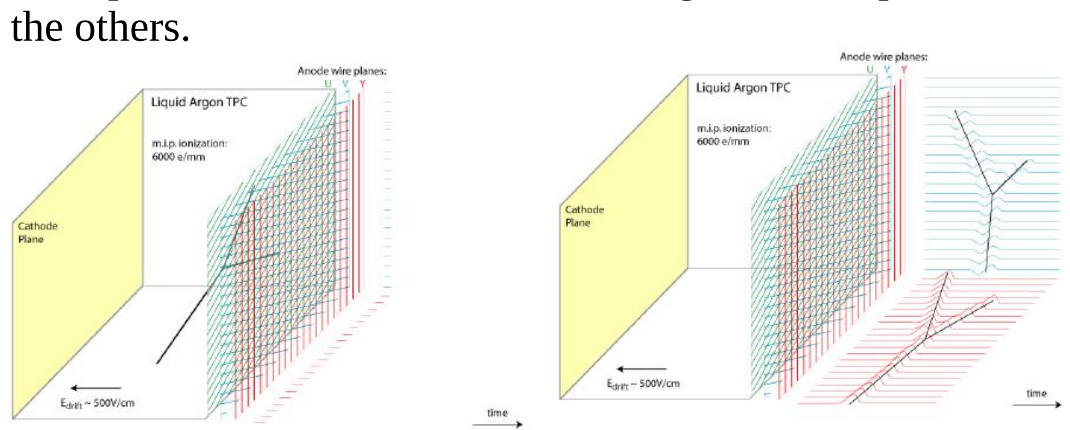


Wire-Cell tomographic event reconstruction aims at an automated event reconstruction for current and future large LArTPCs for neutrino and other underground physics experiments. The philosophy of Wire-Cell strictly follows the principle of TPCs. The reconstruction is directly performed in the 3D space. The reconstruction procedure consists of four components:

- ❑ TPC signal processing
- ❑ 3D event imaging with charge and time
- ❑ 3D pattern recognition
- ❑ Computation of physics quantities

Large Single-phase LArTPC

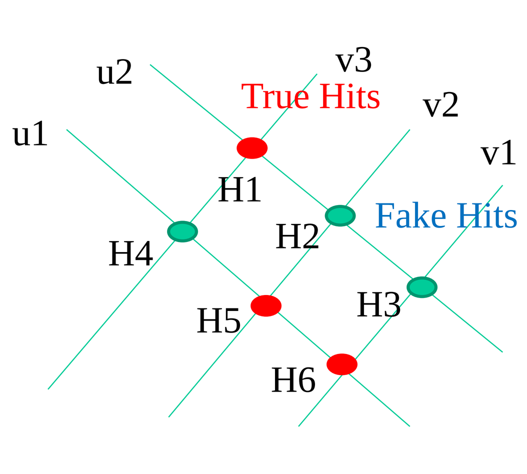
When energetic charged particles pass through the detector medium, they will ionize argon atoms. These ionization electrons are effectively a record of the locations and amount of energy deposited in liquid argon. This record can be extracted from the detector volume by applying an electric field, which will make these electrons drift until they pass through a series of three planes of parallel readout wires. Each plane is oriented at a different angle with respect to the others.



As the charge drifts past the first two planes and is collected on the last plane it produces electrical signals on the nearby wires. These signals are then digitized and recorded. The wire pitch and the sampling frequency coupled with the electron drift velocity give a fine spatial resolution at the scale of a few millimeters.

Challenges with Wire Readout

In colliders, all large gas TPCs utilize pixel readout (i.e. pads). However, this is not suitable for large LArTPCs due to costs associated with large numbers of readout channels and the heat dissipation of the electronics inside the LAr. Wire readout mitigates these problems but introduces challenges for event reconstruction. This is illustrated below with a two-wire-plane example at a fixed time slice:

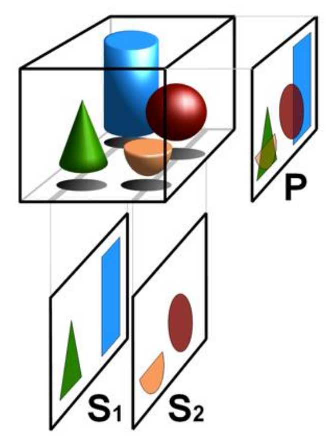


Inherent ambiguities in wire readout, coupled with certain particle trajectories lead to difficulties in determining the amount of charge across a time slice. Steps must be taken to remove as many of the "fake" (ghost) hits while retaining the regions that truly contain charge.

Methods

3D Event Imaging with Charge and Time

One unique feature of TPC with wire readouts is that the same drifting charge is independently measured by each of the wire planes. Wire-Cell begins by removing fake hits using these independent measurements within each 2-us slice of drift time. Then, the 2D time slices are stacked together to reconstruct the 3D event image, similar as in tomography.



Basic principle of tomography (https://en.wikipedia.org/wiki/Tomography)

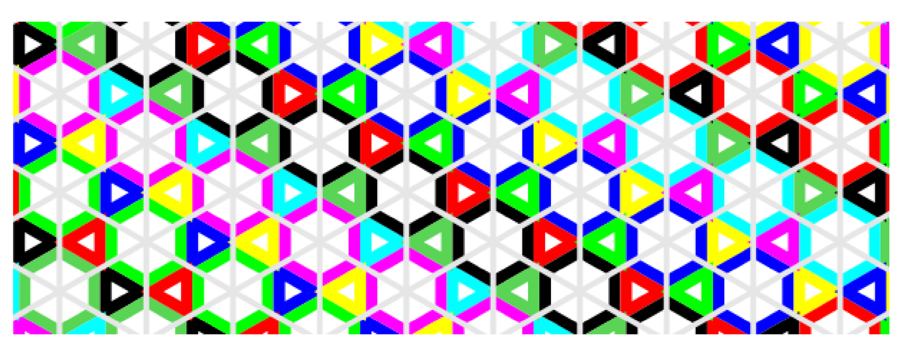
Formally, given the 2-wire-plane example, we have the following matrix equation to connect the measurements (u, v) with the unknown charges (H) at potential locations:

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & a & a & a \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 & a \\ 0 & a & 0 & 0 & a & 0 \\ a & 0 & 0 & a & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{pmatrix}$$

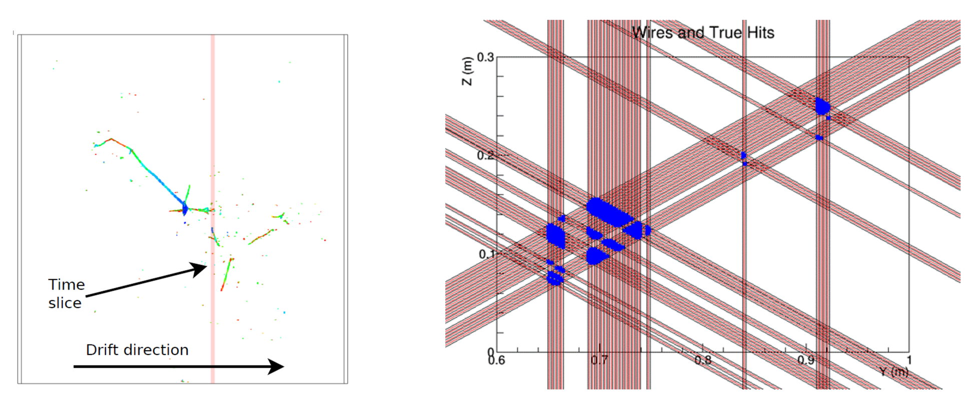
By solving this equation, we obtain the charge at each of the potential hit location. While the true hits would naturally have a sizable charge, the false hits would have charges close to zero.

In practice, the Wire-Cell reconstruction consists of the following steps:

❑ **Tiling**: bin the time slice into "cells", each of which are associated with one wire from each plane.



❑ **Merging**: form "blobs" by grouping together potentially hit, contiguous cells in order to reduce the degeneracy from fake hits.



❑ **Solving**: charge at potential blobs are solved by minimizing the chi-square function formed through comparing the expected and observed charge on wires. When equations can not be directly solved, unlikely blobs are removed to reduce the number of unknowns. Markov Chain Monte Carlo technique is used to reduce the computing time.

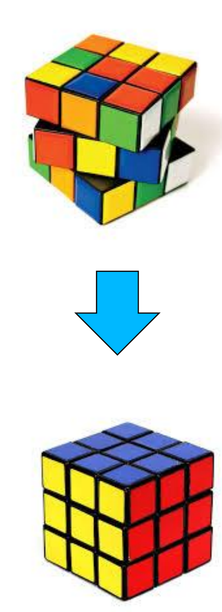
3D Pattern Recognition

Once the 3D image is reconstructed, proper tracking and clustering are performed.

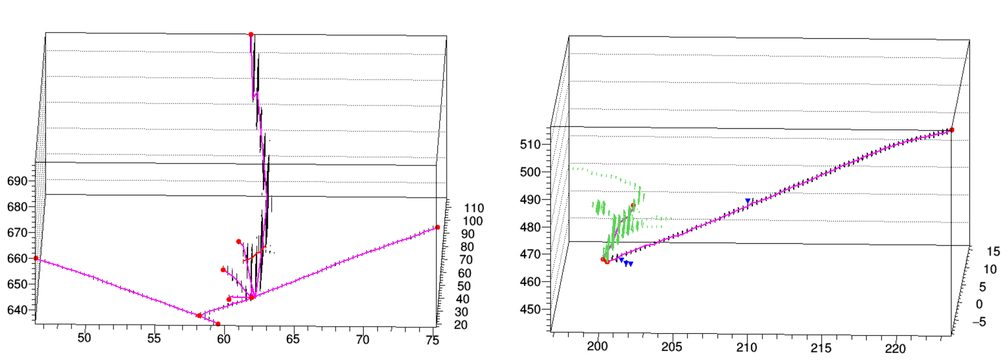
Pattern recognition is challenging because

❑ Algorithms operate on image features which exist at many scales.

❑ Many different event topologies lead to many special case solutions.



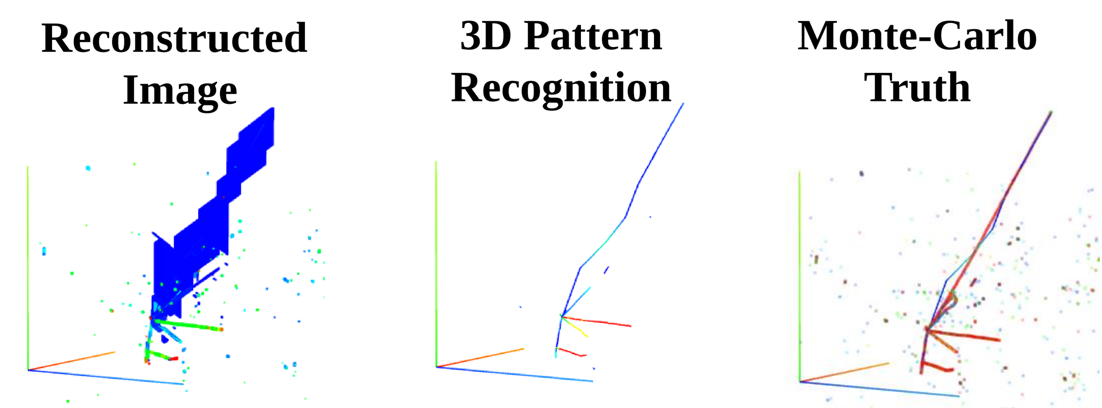
Wire-Cell currently has four topologies: regular tracks, parallel tracks with respect to the wire-plane, shower, and short tracks.

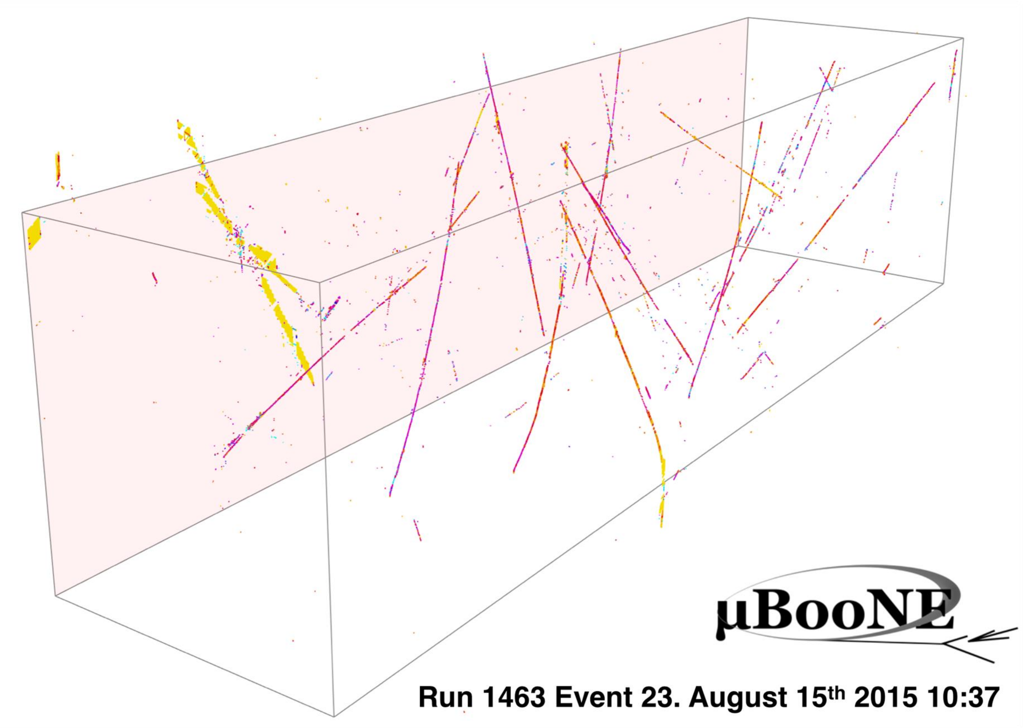


Red vertices, magenta tracks, green showers, blue short tracks

Performances

Wire-Cell has been used on Monte Carlo simulations as well as MicroBooNE commissioning data. The results of Monte Carlo can seen publicly with “Bee” 3D event display: **http://www.phy.bnl.gov/wire-cell/bee/**





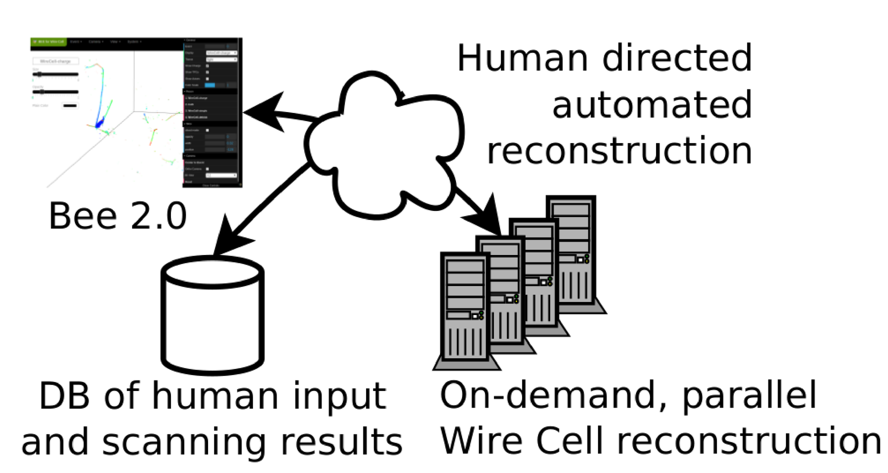
Software and Future Plans

Source: Wire-Cell software is available on GitHub under the “BNLIF” (prototype) and “WireCell” (toolkit and Bee event display) organizations.

Design: The Wire-Cell Toolkit builds on the proven prototype and provides basis for long term development. A comprehensive API makes it easy to integrate with other simulations, data-acquisition output or event processing frameworks..

Parallel: The reconstruction is both CPU and data intensive and thus the software must run in a massively parallel manner. To support this while allowing simple, focused algorithms the “data flow programming” paradigm is followed.

Interactive: Human pattern recognition is very powerful. To leverage this, the “Bee” display will be turned into a “human-directed automated reconstruction” system. It will allow humans to inject judgment in a way that is fully captured and later reproducible. The results of this intervention will be analyzed and fed back in the form of automated improvements.



Future: We believe that further improvements can be made by applying techniques from machine learning and machine vision and we have begun collaborating with experts in these fields.

Acknowledgements

This material is supported in part by the U.S Department of Energy, Office of Science, Office of High Energy Physics, Early Career Program under contract number DE-SC0012704.